Update on LEO Cycling at High DOD

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Photos D.R.

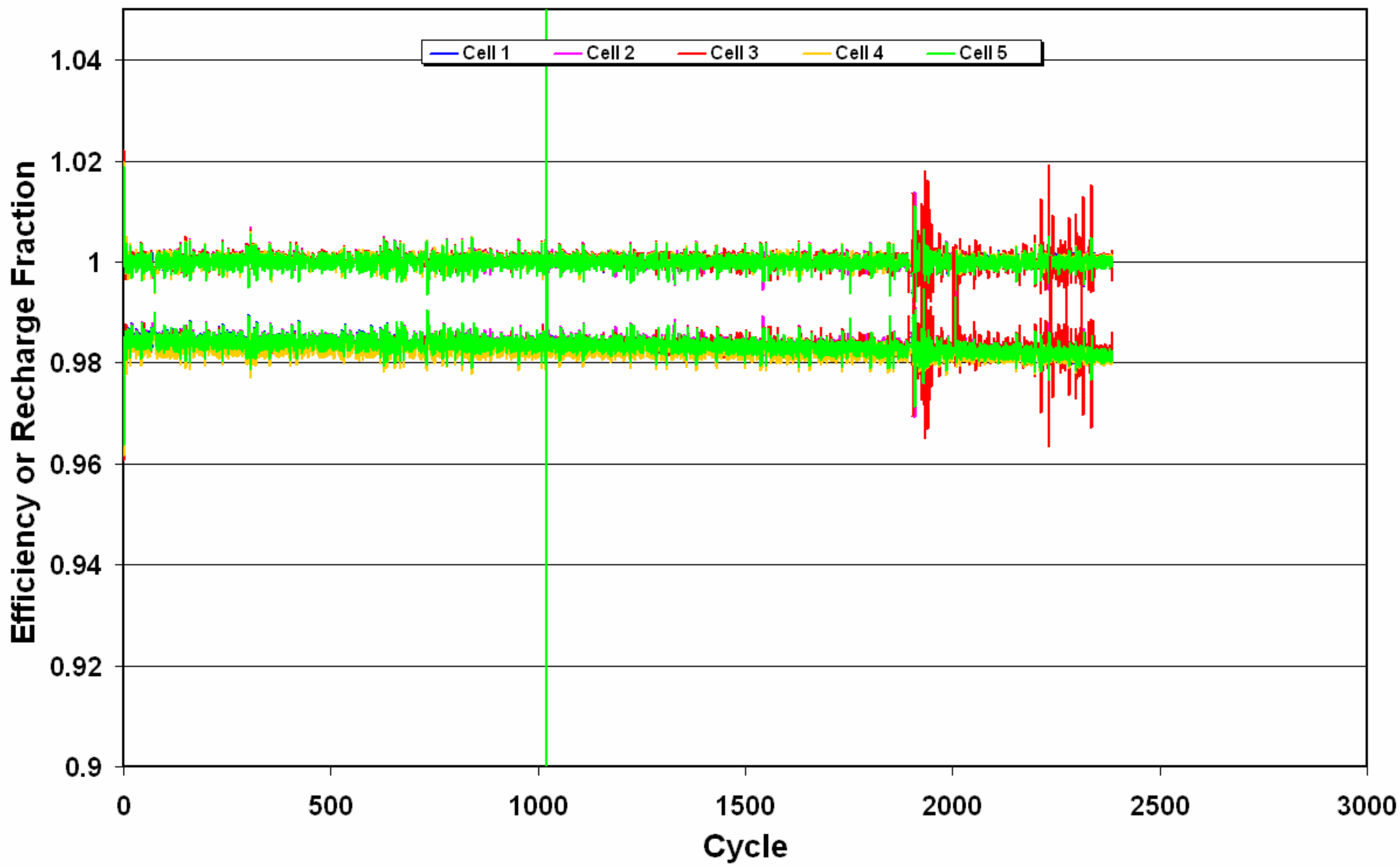
General Remark

- The citations and patents for Li-ion cells, batteries and chemistries dwarf the technical understanding of all other battery systems combined.

- Even with this knowledge bank, the constant, never resting Low Earth Orbit application is a totally unique Li-ion cell application when DOD > 20%. I have over the past 10 years made 6 presentations on LEO, in 2007 at SPW I presented the probable stresses and postulated mechanisms for degradation, including metallic Li deposition at the anode, low self-balancing at the negative, too rapid self-balancing on the positive, probable Li ion concentrations in the electrolyte, etc…

- As a consequence we made about 9 material and design changes creating a LEO specific cell called the VL44EL that shows extraordinary roundtrip energy efficiency.

Coulombic and Energy Efficiency Aerospace Data on LEO testing



Follow NRO/Aerospace Test Method

Saft DOD %	Ah Discharged	EOCV	Rationale[2]
33.33 (40)[1]	14.67Ah	3.9V	~ 50Wh/kg
33.33 (40)[1]	14.76Ah	4.0V	~ 51Wh/kg, >V
33.33 (40)[1]	14.76Ah	3.9V	10% higher I_{ch}
33.33 (40)[1]	14.76Ah	3.9V	20% higher I_{ch}
25 (30)[1]	11Ah	3.9V	~ 38Wh/kg
25 (30)[1]	11Ah	4.0V	~ 39Wh/kg, >V
40 (48)[1]	17.6Ah	3.9V	~ 59Wh/kg

Orbital times: Discharge = 35min; Charge = 61min 15cycles/day

[1] DOD in () follows the definition capacity = 5/6 Cell Nameplate

[2] The convention is to specify the energy density in Wh/kg delivered each cycle at cell level, this gives the best comparison, not EODV at a given DOD.

5500 Cycles Rationalization (1 year)

DOD %	EOCV	Cycling Energy Density	% Wh loss @6000 cy	Effect on loss
40[1] I_{ch} 16.24A	3.9V	~ 50Wh/kg	4.77(av. 5)	baseline
40[1] I_{ch} 16.24A	4.0V	~ 51Wh/kg, >V	9.34(av. 3)	95%
40[1] I_{ch} 17.86A	3.9V	10% higher I_{ch}	7.21(av. 2)	51%
40[1] I_{ch} 19.50A	3.9V	20% higher I_{ch}	8.66(av. 2)	82%
30[1] I_{ch} 12.17A	3.9V	~ 38Wh/kg	3.13(av. 3)	baseline
30[1] I_{ch} 12.17A	4.0V	~ 39Wh/kg, >V	5.50(av. 2)	75%
48[1] I_{ch} 19.50A	3.9V	~ 59Wh/kg	12.30(av. 2)	

[1]DOD follows the definition capacity = 5/6 Cell Nameplate

Wh loss is the 4.1V diagnostic capacity @ C/2 to 3V

Calendar Effect Is Small Compared to Cycling Effect

Time at 3.9V	Wh (av. of 2 cells)	% loss	Ah	% loss
0	158.50	0	43.48	0
270 days, 4050 cycles	156.23	1.4%	43.11	0.84%

Time at 3.7V	Wh (av. of 2 cells)	% loss	Ah	% loss
0	159.9	0	43.90	0
270 days, 4050 cycles	158.81	0.68%	43.69	0.48%

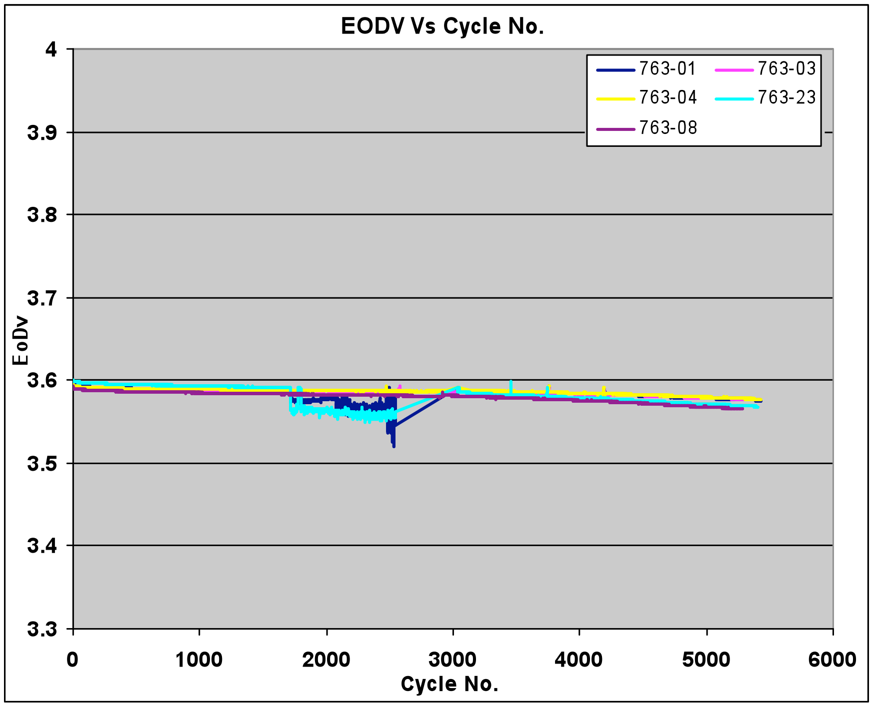
Rationalization

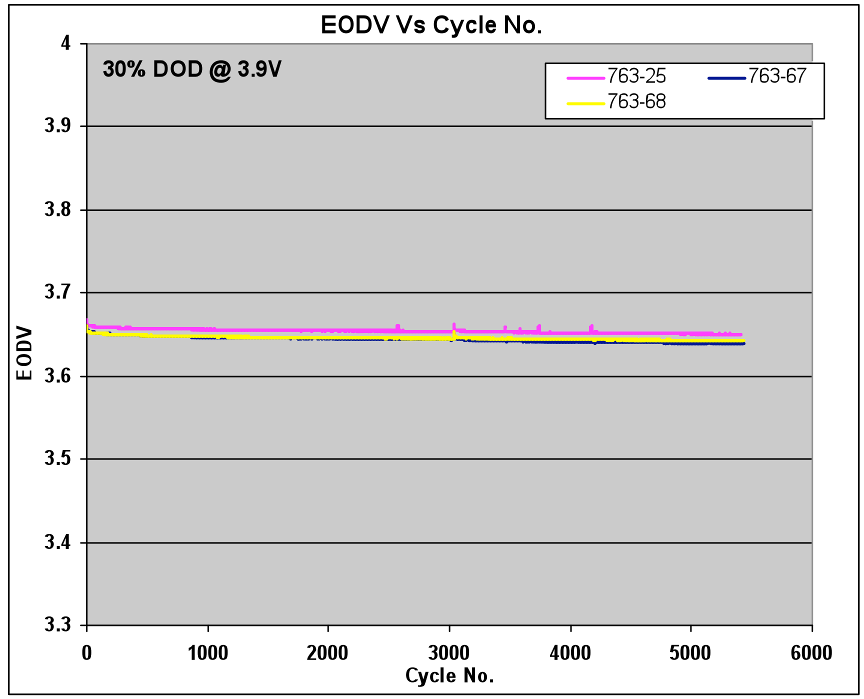
- **When we move to a higher EOCV, 4.0V versus 3.9V per cell we degrade the cell faster; Conclusion: start at the lowest EOCV possible, the effect of 4V for 30% DOD is less compared to 40% DOD, probably due to a two variable interaction. The charge current is lower for 30% DOD and probably compensates the 4V effect.**

- **10 or 20% Higher charge currents rates are deleterious for a constant DOD; Conclusion: the maximum current chosen is important and conversely the higher charge currents allow a lower taper current at the EOC. The absolute value of the charge current is the important parameter interacting with the EOCV limit.**

- **48% DOD at EODV = 3.9V degrades faster than expected. The same 19.5A was used for the 20% higher current for 40% DOD and for the 48%DOD test. Another factor is operating, DOD?**

40% and 30% DOD @ EOCV = 3.9V

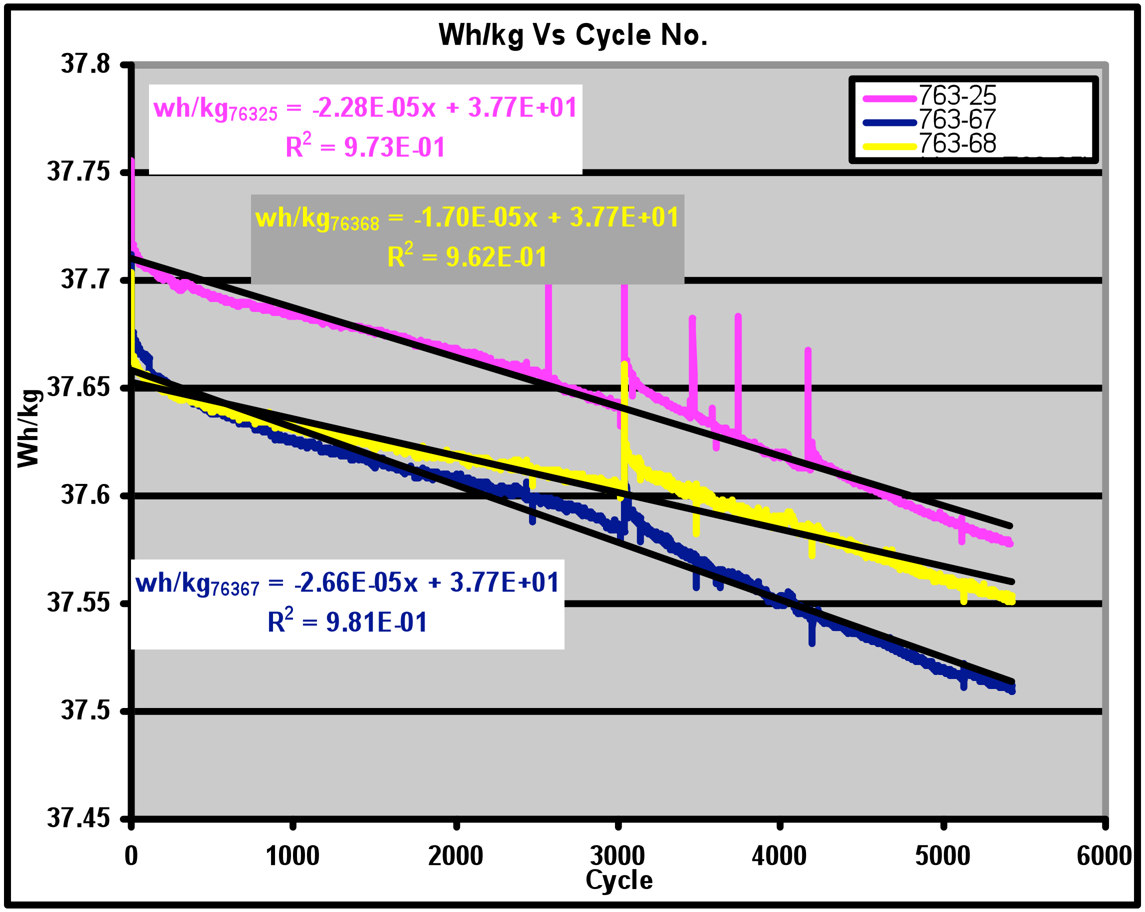




40% DOD

30% DOD

A different way to look at rundown, track Wh/kg loss: 30%DOD case (3.9V)



Taking Wh/kg loss per cycle to 50,000 cycles

	Loss rate in Wh/kg per cycle	BOL Energy in Wh/kg delivered per cycle	EOL Energy in Wh/kg; 50,000 cycles (9.1 years use)
30% DOD	$-2.2x10^{-5}$	38 Wh/kg	36.9 Wh/kg
40% DOD	$-4.2x10^{-5}$	50 Wh/kg	47.9 Wh/kg

Biggest assumption above is Wear Mechanism stays the same

Conclusions

- **After one year of testing, capacity measurements clearly show that higher EOCV 4v vs. 3.9V and higher charge current (10 and 20% higher) are deleterious to capacity and energy retention at full SOC at 4.1V @ C/2 rate to 3V.**

- **Wk/kg per cycle losses deduced appear reasonable and predict long life assuming the same wear out mechanism operates over life.**

- **A second confirmation lot has been built and cycling has been started, the capacity, Wh and impedance show agreement to the first build, and now we will have two separate build lot to compare and contrast, adding to the predicative confidence of the VL44EL cell for LEO use.**